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Salt-marsh sediment

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Sand in the salt marsh: contribution of high-energy conditions to back-barrier salt-marsh accretion

Alma V. de Groot, Jan P. Bakker

Abstract

The environmental dynamics at barrier-island salt marshes are reflected in lateral and vertical textural patterns of the marsh sediment. This chapter describes the occurrence and importance of sand, the sedimentary result of high-energy conditions, for the building of salt marshes that otherwise consist of fine-grained sediment. The study was carried out on the islands of Schiermonnikoog (NL), Terschelling (NL) and the peninsula of Skallingen (DK). Firstly, we recorded the presence of sand in the sediment representing early salt-marsh formation. The results indicate that part of the salt marsh developed under conditions that were dynamically enough for sand to be transported. The spatial distribution of these conditions depends on soil elevation and location on the marsh, modified by the presence of artificial sand dikes. Further we recorded the presence and thickness of sand layers within the salt-marsh deposits. Sand layers are found on twenty percent of the marsh area and are mainly located along marsh creeks, the salt-marsh edge and associated with washovers. In total, sand contributes less than ten percent to the volume of marsh deposits on Schiermonnikoog. We crudely dated the layers using the thickness of the deposits and known marsh age. The ages of the layers indicate that storms capable of depositing sand in the salt marsh occur every decade or so, but the local hydrodynamics and availability of sand determine whether a site receives sand or not.

Upper photo: sand on the eastern sand flat of Schiermonnikoog, ready to be blown into the salt marsh.

Lower photo: During high-energy conditions, waves are able to stir up sand and erode lumps of salt-marsh sediment from the marsh edge.

6.1 Introduction

The natural dynamics characteristic of barrier islands have recently drawn attention in relation to the concern for the conservation of specific ecosystems and biodiversity, coastal protection and island response to (global) sea-level rise. The resilience of the coast and its ecosystems is thought to increase by allowing a certain degree of natural dynamics in the coastal zone, as opposed to fixing the coast with engineering works. When applying management that aims at preserving these dynamics (e.g. Samenwerkingsverband Het Tij Geleerd, 2007b), knowledge on the magnitude of the natural dynamics is essential.

Along the North Sea, barrier-island salt marshes generally consist of fine-grained sediment: mud and silt. These reflect the generally sheltered conditions under which the marshes develop. However, the grain-size distribution of the deposited sediment varies because of variations in energy conditions associated with tidal and seasonal periodicity and the occurrence of storms. This is reflected in lateral heterogeneities in sediment as well as textural variations in the vertical stratigraphy (Wheeler et al, 1999; Allen and Haslett, 2002). During high-energy conditions, coarse-grained material, sand, may be deposited on the salt marsh (Ehlers et al., 1993). Because these events occur infrequently, the deposits form layers with coarser grains in the profile, forming records of the dynamics of the salt-marsh environment. Erosion of fine-grained sediment from the marsh surface during storms is generally negligible in this type of marshes (Friedrichs and Perry, 2001).

Storm-related coarse-grained layers and sand deposits are reported from various marshes and locations on the marsh, where the individual references mostly report layers from one marsh location. Firstly, sand laminae were observed thinning out from the creek levees (Van Straaten, 1954), deposited when the velocity of the flooding water decreases so that sand settles out. Secondly, sand layers are observed along the salt-marsh edge, sometimes taking the form of ridges that follow the salt-marsh edge or cliff (Van Straaten, 1954; Ehlers, 1988b; Ehlers et al, 1993; Eisma and Dijkema, 1997; Wheeler et al, 1999). The sand is deposited when the marsh vegetation dampens waves and currents coming from the intertidal flats (Möller et al, 1999; Neumeier and Amos, 2006). Thirdly, sand layers may be the result of overwash. During these conditions, the marshes are not only inundated from the back-barrier area, but also from the open sea through gaps in the dunes (Ehlers et al, 1993; Oost and De Boer, 1994; Flemming and Davis, 1994; Donnelly et al, 2006; Nielsen and Nielsen, 2006a). The construction of artificial sand dikes has blocked the potential sand supply from overwash on many islands in the Wadden Sea. This may have lead to the loss of marsh surface as washover sediment contributes to the building of salt marshes on barrier islands (Godfrey and Godfrey, 1974; Ehlers, 1988b; Eleveld, 1999). Finally, aeolian transport may add sand to the salt marsh (French and Spencer, 1993; Reineck and Gerdes, 1996).

In general, the coarse-grained deposits from high-energy events are considered to be less important for salt-marsh building than the deposition from clays and silts from

non-storm conditions (Wheeler et al, 1999). However, the relative importance of sand to total salt-marsh sedimentation and its spatial distribution within a single marsh are not clear from the previously mentioned studies. The same holds for the relative importance of the direct sources: back-barrier area, creeks, beach and dunes. This means that the effect of for instance the widespread past construction of sand dikes is hard to quantify. Another remaining question is whether sand deposition remains constant during the evolution of a salt marsh.

The purpose of this study is to reconstruct the dynamics of salt-marsh sedimentation on barrier-island salt marshes and quantify the importance of sand for salt-marsh sedimentation. For that, we will describe the spatial patterns and the magnitude of the contribution of sand to salt-marsh sediment. We will start with the importance of sand during the initial stage of salt-marsh formation. Subsequently, we will focus on the occurrence of layers deposited during further growth of the marsh and date these deposits using the available data of marsh age and net accretion. We present field data from three barrier-island salt marshes in the international Wadden Sea. The work starts with describing the patterns on the scale of the entire marsh, and subsequently zooms in on selected sites to identify the sources of the sand.

6.2 Methods

6.2.1 Study sites

The main study area is the Dutch barrier island of Schiermonnikoog. Additional measurements were done on Terschelling (NL) and Skallingen (DK). A description of the islands is given in Chapter 2.

6.2.2 Measurements

The presence of sand within salt-marsh sediment was described from sediment cores taken with a small soil corer, as described in detail in Chapter 2. From the cores, information on the environmental conditions during initial salt-marsh development was derived from the amount of sand mixed into the lower part of the fine-grained marsh sediment, given by the type of transition between the top and base layer (sharp, intermediate or gradual, see Chapter 2). All fine-grained sediment is considered to be deposited when the site was salt marsh, as such layers are only seldom found on the present intertidal flats and beach plains. If sand is mixed within the fine-grained material, as is the case in gradual transitions, the sand was assumed to be deposited while the site was already a salt marsh. Sharp transitions represent a rather abrupt change from high-energy conditions in which only sand can settle, to low-energy conditions in which sand is not transported and mud is able to settle. Conditions during initial marsh formation were thus calm. Gradual contacts are the sedimentary result of conditions under which (often very fine) sand as well as fine-grained sediment is transported and deposited. These conditions during initial marsh formation were thus more dynamic.

Sand layers higher in the profile were used as record of past storms. Their thickness was used to identify the contribution of sand to the total salt-marsh sediment budget. The number and thickness of layers within the top layer were determined from the core descriptions.

Soil elevation, base elevation, marsh age and the geographical coordinates at the measurement locations were measured as described in Chapter 2. Data analysis was carried out using MS Excel and Surfer (version 8.00, Golden Software, 1999). Aerial photographs of the study area from several years were used as reference.

In this chapter, the salt marsh is defined as the vegetated area with a fine-grained top layer of at least 0.5 cm thick. All measurements without a fine-grained top layer, i.e. creeks, intertidal flats and dunes, were excluded from the analysis.

Dating sand layers

Storm layers on other European marshes were dated successfully using ^{137}Cs (Ehlers et al, 1993; Wheeler et al, 1999). Such data are not available for our study sites. Therefore we used a simplified approach as explorative analysis, by determining the ages of the sand layers from the depth of the sand layers within the top layer and marsh age. For this, we assumed that accretion rates are constant but location-dependent. This is a considerable simplification, as accretion rates are generally exponentially declining with time (Olff et al, 1997; Allen, 2000; Van Wijnen and Bakker, 2001; Temmerman et al, 2003). However, the available models that describe accretion on Schiermonnikoog (Olff et al, 1997; Van Wijnen and Bakker, 2001) are well suited for generalisation and long-term marsh behaviour, but not for point-by-point hindcasting in small time steps, as we want to do here. Furthermore, the error introduced by using linear instead of exponential accretion rates is most probably comparable to the uncertainties in marsh age and layer thickness. The consequence of the assumption of constant accretion rates is that the age of the sand layers is generally underestimated.

For each location on the 'grid' and the catchment (see below), the net accretion rate was determined using:

$$\text{net accretion rate} = \frac{d_x}{t_{\text{measurement}} - t_0} , \quad (6.1)$$

in which d_{top} is top-layer thickness, $t_{\text{measurement}}$ is the year of measurement and t_0 is the year in which the marsh development started (Figure 6.1). We calculated the year of sand deposition (t_{sand}) from the time in which the top layer underneath the sand layer (with thickness d_x) was deposited:

$$t_{\text{sand}} = t_0 + \frac{d_x}{\text{net accretion rate}} . \quad (6.2)$$

Some of the cores contained more than one sand layer. In these cases all sand layers were dated individually. The accuracy of t_{sand} is a few years for young marshes and decreases to about 20 year for older marshes.

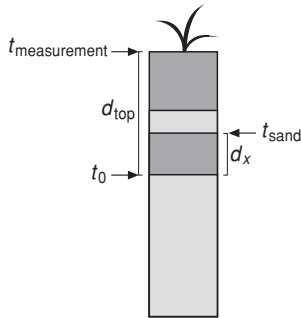


Figure 6.1. Dating of the sand layers. The figure is a cross-section of a sediment core, containing fine-grained layers (dark) and sand layers (light). See text for further explanation.

We compared the calculated age of the layers with the records of yearly maximum water levels (Rijkswaterstaat, 2008), which serve as indication for the occurrence of storms. Because the time series for Schiermonnikoog did not cover the entire period of interest, additional data from Harlingen are given, which is located 60 km to the west in the Wadden Sea and has comparable water levels to Schiermonnikoog ($R^2 = 0.74$ for water levels from Schiermonnikoog and Harlingen).

6.2.3 Measurement layout

The cores were taken in various measurement layouts between 2003 and 2007 (Figure 6.2). We start with measurements at the scale of the entire marsh on Schiermonnikoog, after which we zoom in on a selected catchment (i.e. the area connected to one creek and its branches) and then on sites close to potential sand sources, which are the high-middle marsh (on all islands) and the salt-marsh edge. The chronosequence on Schiermonnikoog allowed comparison between marshes of various ages and may provide information on the temporal variation in sand deposition.

Salt-marsh landscape

Patterns on the scale of the entire salt marsh were described using measurements in a large grid over the salt marsh of Schiermonnikoog that developed after 1900 ('grid' in Van Wijnen and Bakker, 2001). It consists of transects 200 m apart, perpendicular to the salt-marsh edge, on which every 50 m a measurement point is located ($N = 597$, Figure 6.2). At every measurement point, up to three cores and elevation recordings were taken within 1 m^2 , which were averaged. The spacing of the grid is relatively large compared to the geomorphology of the marsh, hence the following zooming in on selected sites.

Catchment

Patterns on a smaller scale were described from a young catchment on Schiermonnikoog, which has always been outside the influence of the sand dike. The catchment (approximately $400 \text{ m} \times 500 \text{ m}$) is situated in the east of the salt marsh and started to develop around 1980 (Figure 6.2). A larger creek on the western side of the

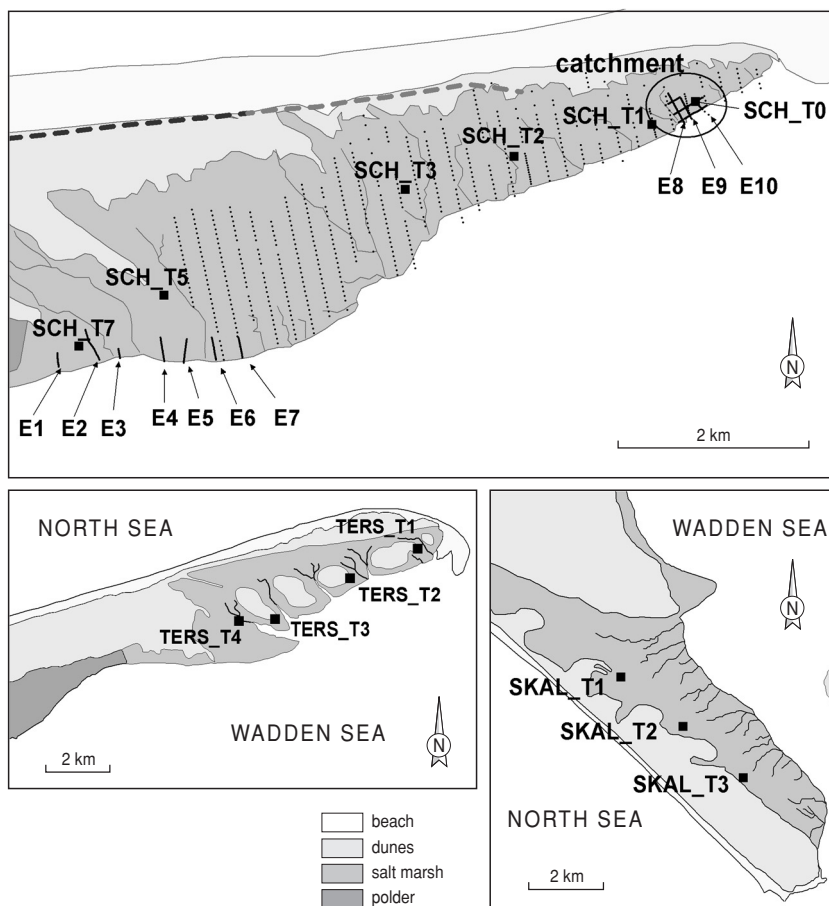


Figure 6.2. Measurement locations on Schiermonnikoog, Terschelling and Skallingen, see the text for explanation. The original location of the artificial sand dike on Schiermonnikoog is given by the dashed line, the part that is still present in dark grey and the by now reworked part in light grey.

study area extends into an overwash channel. Cores were taken every 5 m along six transects, three perpendicular to the salt-marsh edge and three parallel to it, resulting in a total of 300 data points.

High-middle marsh

Sand from dunes and washover is expected on the high and middle salt marsh. On these locations, measurements were carried out on transects consisting of adjacent measurement plots of 1 m × 1 m, arranged in a 10 m wide and 40 to 68 m long array. In every plot, one recording of top layer and soil elevation was taken. The transects were laid out from the dune foot to the middle marsh and were all located on comparable base elevation. Some transect locations have always been in the shelter of an arti-

Table 6.1. Characteristics of the high-middle marsh sites.

island	name	year of vegetation establishment	sheltered by artificial sand dike	
			during marsh formation	during further marsh growth
Schiermonnikoog	SCH_T0	1995	-	-
Schiermonnikoog	SCH_T1	1984	-	-
Schiermonnikoog	SCH_T2	1974	yes	only in beginning
Schiermonnikoog	SCH_T3	1957	yes	only in beginning
Schiermonnikoog	SCH_T5	1900	-	only later
Schiermonnikoog	SCH_T7	1850	-	only later
Terschelling	TERS_T1	1925 – 1940	yes	yes
Terschelling	TERS_T2	1925 – 1940	yes	yes
Terschelling	TERS_T3	1925 – 1940	yes	yes
Terschelling	TERS_T4	around 1920	partly	yes
Skallingen	SKAL_T1	1900 – 1930	-	only later
Skallingen	SKAL_T2	1900 – 1930	-	only later
Skallingen	SKAL_T3	1900 – 1930	-	only later

ficial sand dike, some only during part of their development and some have always been outside the shelter of an artificial sand dike. Six transects are present along the chronosequence of Schiermonnikoog (SCH_T0 – T7, Figure 6.2 and Table 6.1, see also e.g. Olff et al, 1997; Van Wijnen and Bakker, 2001), four on Terschelling (TERS_T1 – T4) and three on Skallingen (SKAL_T1 – T3). From TERS_T1, TERS_T2, SKAL_T1 and SKAL_T3 only the two outer columns were measured.

Salt-marsh edge

Sand directly originating from the intertidal flats is expected around the salt-marsh edge. Seven transects were established on the old marsh (E1 – E7) and three on the young marsh (E8 – E10) of Schiermonnikoog, all perpendicular to the salt-marsh edge. Part of the transects are included in the catchment. Top-layer thickness and soil elevation were measured every 5 or 10 m along transects of between 100 and 350 m long.

6.3 Results

6.3.1 Initial salt-marsh development

On the scale of the *entire salt marsh*, the proportions in which the sharp, intermediate and gradual transitions occur are approximately equal. Even though the three cores taken per measurement location do not always have the same transition type, still a large-scale pattern emerges. Sharp transitions, reflecting calm conditions during initial



Figure 6.3. Distribution of transitions types over the post-1900 salt marsh at the landscape scale on Schiermonnikoog ('grid'). The symbols give the dominant transition type from three observations per measurement location ($N = 597$). The original location of the artificial sand dike is given by the dashed line.

marsh formation, are mostly found at the middle part of the salt marsh and in areas that developed while they were protected by the artificial sand dike (Figure 6.3). These locations are at the low and middle part of the base-elevation gradient (upper panel of Figure 6.4). Towards the intertidal flats, coinciding with low base elevations, the sharp transitions give way to gradual transitions that reflect more dynamic conditions during initial marsh growth. Gradual transitions along the marsh edge are especially often found where the marsh has been laterally extending southwards (c.f. Figure 2.10). At high base elevations along the northern fringe of the marsh, intermediate and gradual transitions dominate.

The percentage of sharp transitions is highest on marshes that developed around the time the artificial sand dike was finished (age classes 1955 and 1964 in lower panel of Figure 6.4). In marshes that established later, the percentage of sharp transitions decreases in favour of the gradual transitions. These gradual transitions are mostly associated with the marshes that developed east of the protecting influence of the sand dike and south of already existing marsh area in the western part of the study area.

Within the *catchment* on the young marsh that formed in the lee of a large dune, sharp transitions dominate and conditions were thus on average calm (Figure 6.5). Gradual transitions are mainly found around the salt-marsh edge and in depressions with developing creeks.

On the local scale, there are large differences in the proportions of sharp, intermediate and gradual transitions. At the *high-middle salt marsh*, the transition types gener-

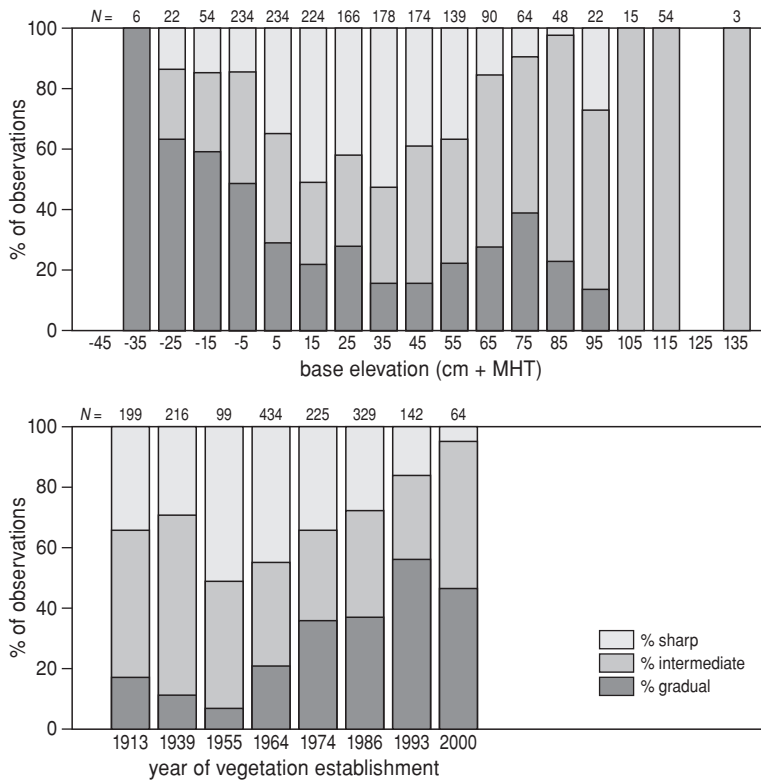


Figure 6.4. Percentage of transition types in cores at the landscape scale (large-scale grid) on Schiermonnikoog, given per base elevation class (upper panel) and per year of vegetation establishment (lower panel). The numbers represent the number of individual observations in that class.

ally form patches of several metres across (Appendix 6A). The proportions in which they occur differs between the transects. The patterns cannot be explained by variations in soil or base elevation at the same scale. On Terschelling, the conditions during initial marsh formation were calm in the transects that developed in the lee of the sand dike (TERS_T1 and TERS_T2). At the transects that developed close to a largest creek, which was a washover channel before the building of the sand dike, the conditions were rougher (TERS_T3 and TERS_T4, Ten Haaf and Buijs, 2008). The transects on Skallingen have relatively many sharp transitions. These locations developed relatively far from the salt-marsh edge, in the lee of a large dune area which was at that time cut through by washovers but created even then a sheltered environment. These results all confirm the shelter from dynamics formed by dunes and artificial sand dikes.

Along the *salt-marsh edge*, gradual and intermediate transitions dominate (Appendix 6B). The shape of the cross-sections or the dominance of lateral accretion or erosion are not related to the patterns of transition types.

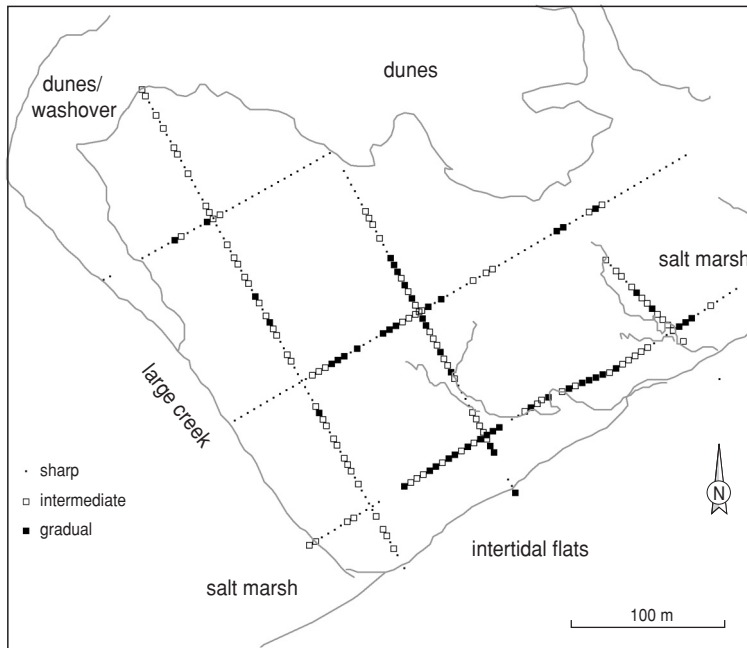


Figure 6.5. Distribution of transition types at the young catchment on Schiermonnikoog (Figure 6.2, $N = 300$).

6.3.2 Sand layers

Salt-marsh landscape

On the scale of the entire marsh, twenty percent of the measurements contain one, or sometimes more, sand layers (Figure 6.6). Not all three points within 1 m^2 always have the same number and thickness of layers. The highest number and thickness of sand layers are present around the salt-marsh edge and, to a smaller degree, creek levees. These sites are often associated with low base elevation, so that also both the number of layered measurements and the number of layers per core decrease with increasing base elevation (left panel of Figure 6.7). At the high marsh, sand layers are rare or absent, which coincides with the upper limit of the sharp transitions (Figure 6.4). Some of the creeks (the 4th, 5th, 6th, 8th, 11th and 13th creek) are associated with thicker sand deposits than the other creeks (lower panel of Figure 6.6). These specific creeks have overdeepened throats and are flanked by circular dunes at the side of the North Sea, indicating that these parts act as overwash channels during storms and consequently that at least part of these sand layers are washover deposits.

The thickness of the sand layers expressed as contribution to the thickness of the top layer is only marginally related to base elevation. Sand contributes mainly to the top layer at marsh developed at base elevation lower than $70 \text{ cm} + \text{MHT}$. The contribution is highest between base elevations of 20 and $60 \text{ cm} + \text{MHT}$ (right panel of

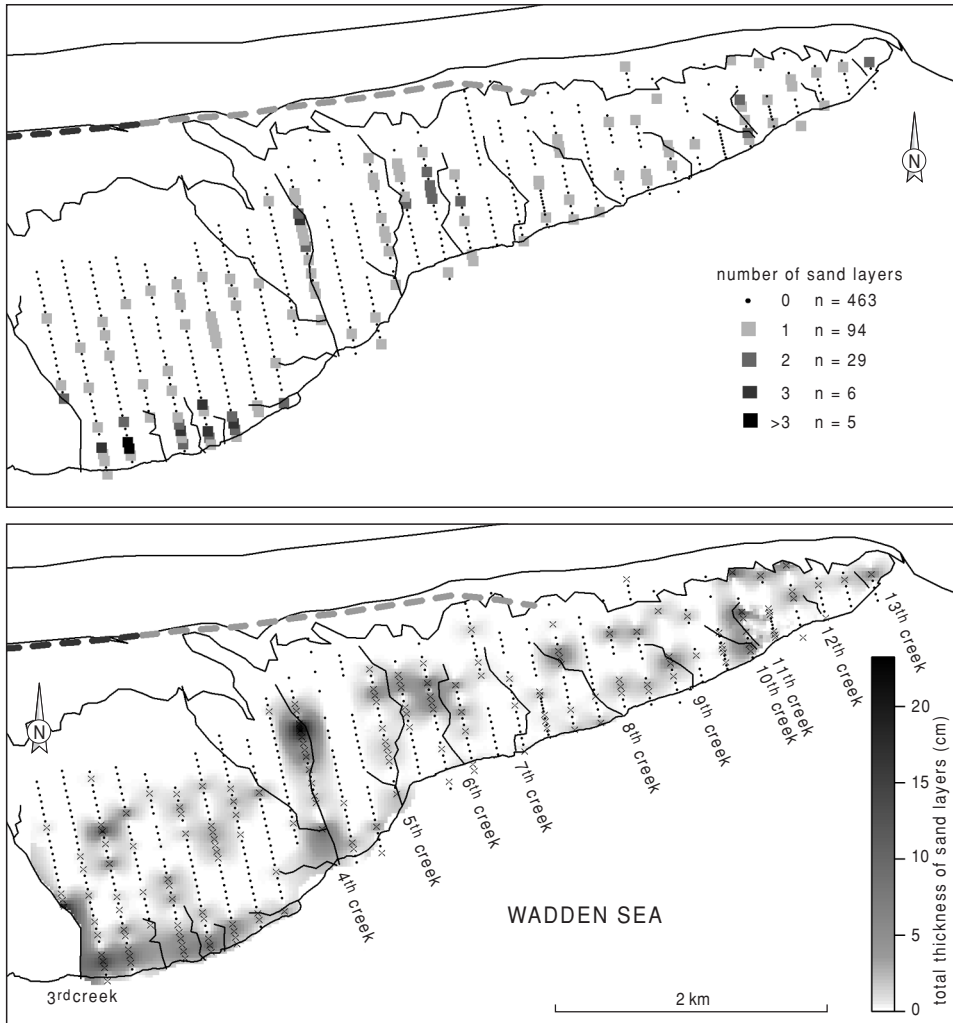


Figure 6.6. Upper panel: average number of sand layers within the top layer at the landscape scale of Schiermonnikoog. Lower panel: thickness of sand layers within the fine-grained top layer.¹ Crosses indicate layered locations.

Figure 6.7). The total contribution of sand to the marsh top layer was determined by comparing the interpolated thickness of all sand layers (Figure 6.6) with the interpolated top-layer thickness over the entire study area. The total contribution of sand is somewhat under ten percent of the total volume of marsh deposits.

¹ In the upper panel of Figure 6.6, the average number of sand layers is only shown if at least two out of three cores on a location contain a sand layer. The lower panel (average sand thickness) also includes locations where in only one of the cores a relatively thick sand layer was found. The second method leads to a larger number of layered sites.

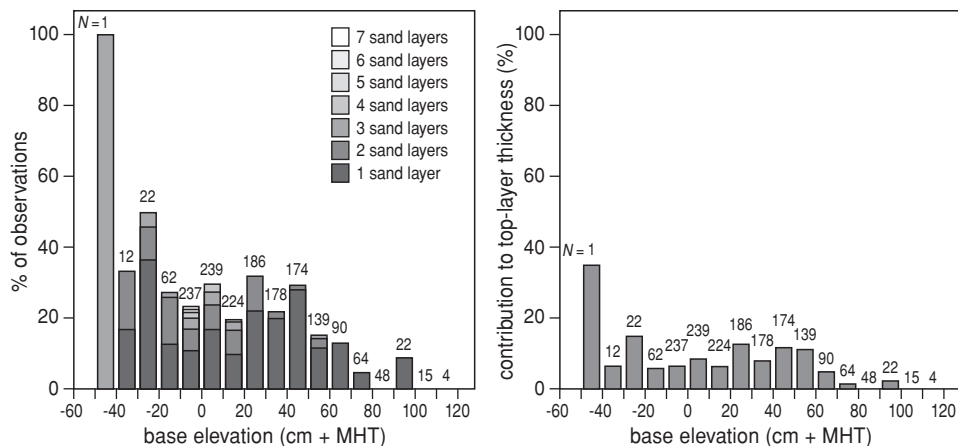


Figure 6.7. Percentage of salt-marsh sites on the landscape scale on Schiermonnikoog that contain sand layers within the top layer (left panel) and the volumetric contribution of these layers to the top layer (right panel), as percentage of all observations per base-elevation class. The numbers in the bars represent the number of observations within each base-elevation class; note that the lowest base-elevation class contains only one observation.

At the individual measurement points, most sand layers are situated relatively deep within the top layer, and were therefore deposited when the marsh at that location was young. Around the salt-marsh edge and creeks, where multiple sand layers occur, the layers are distributed through the entire top layer. The threshold for sand transport at these sites can therefore be reached at any age of the marsh.

The ages of the sand layers, determined from their depth within the top layer and marsh age, are given in Figure 6.8. This shows that the layers were deposited during several individual events, each at a different location on the marsh. The spatial pattern is somewhat obscured by the uncertainties in marsh age (the classes cover on average 10 years) and accretion rate. Nevertheless, the interior marshes between the 3rd and 4th creek clearly contain much older layers than elsewhere on the marsh. The development of these interior marshes started before the artificial sand dike was constructed in 1959 and these marshes have not received sand since, pointing towards overwash as the source of the sand. Later, new marshes developed southward of the already existing marshes between the 3rd and 4th creek (c.f. Figure 2.10). The age of these layers decreases with decreasing marsh age. In this area, the sand from the salt-marsh edge was deposited within a limited distance from the intertidal flats. The number of deposited sand layers increases after 1965. The increase can be mainly attributed to new marsh that developed seaward of existing marshes and new marshes east of the 4th creek, where the protecting sand dike was breached and reworked or, further east, never present.

We compared the calculated age of the layers with the records of yearly maximum water levels, taking into account the accuracy of the calculated ages (which decreases

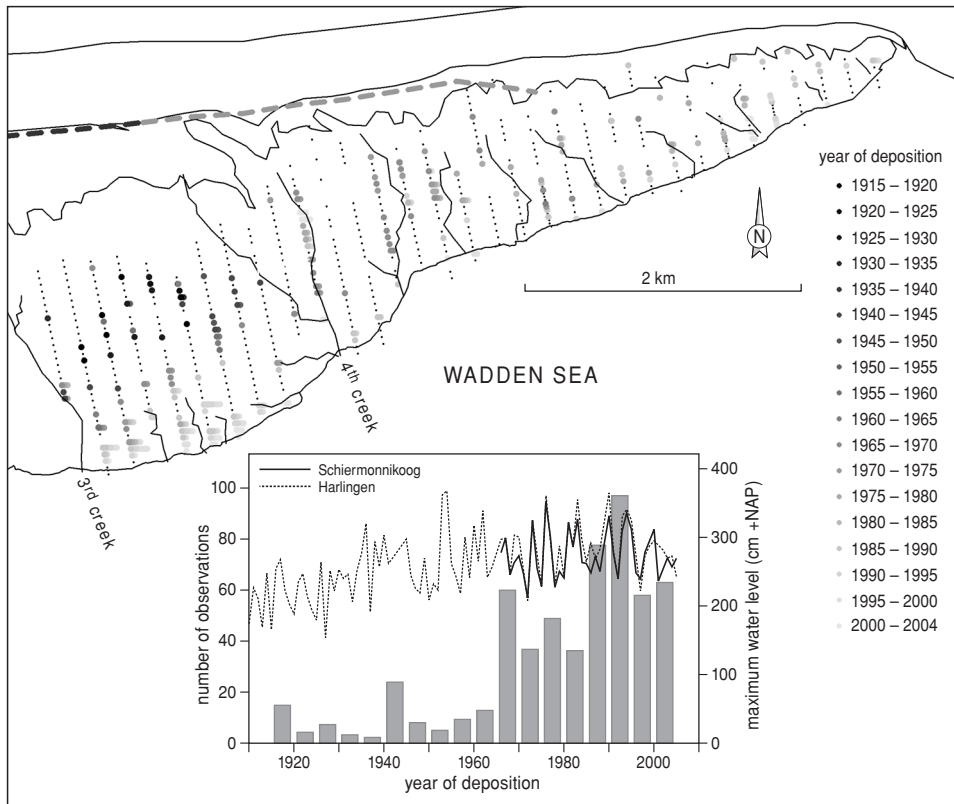


Figure 6.8. Map and histogram of the years of deposition of sand layers on the landscape scale of Schiermonnikoog. If several layers were present in the profile, these were plotted adjacent to the measurement point, with the deepest layers on the left. The lines in the graph represent yearly maximum recorded water levels for Schiermonnikoog and Harlingen (60 km west of Schiermonnikoog, Rijkswaterstaat, 2008).

with increasing age) and that the method tends to underestimate the age of the sand layers. The sand layers may be related to high tides in 1917, 1936, 1962 (perhaps), 1973 (perhaps), 1976, 1990, 1994 and 2000. From at least the storm in 1976 it is known that sand was deposited on the island during overwash (Ten Haaf and Buijs, 2008). The elsewhere catastrophic flood of 1953 is not reflected in the sand layers.

Whether the environmental conditions change during marsh evolution was explored by overlaying the transition types with the occurrence of sand layers (Figure 6.9). Of all points with gradual transitions, one quarter also has sand layers and of all points with sand layers, one third has a gradual transition. This indicates that the conditions during the early stages of salt-marsh formation are not indicative for whether a site will receive sediment from high-energy events later.



Figure 6.9. Overlay of the occurrence of sand layers within the top layer (grey) and gradual transitions (crosses) on the landscape scale on Schiermonnikoog. Small dots represent measurements without sand layers that have a sharp or intermediate transition.

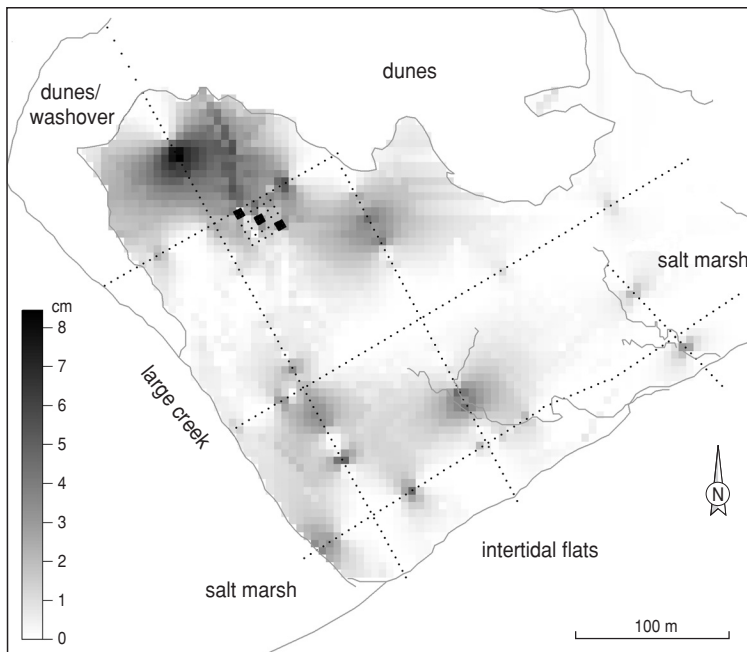


Figure 6.10. Interpolated total thickness of sand layers (lower panel) at the young catchment on Schiermonnikoog (Figure 6.2). Dots represent measurement points.

Catchment

Within the young marsh catchment, a third of the area contains sand layers, in most cases only one layer. The sand patches are located in the north-west and middle of the area, along the larger creek (extending into an overwash channel) and smaller creeks, and in the lee of a small ridge that is developing in the southern corner (Figure 6.10). The layers appear to be deposited in at least two phases, outlined in Figure 6.11. The older deposit in the north-west of the site may be related to one of the storms in 1976, 1981 or 1983. The younger deposit in the middle of the area was probably deposited in 1990 or 1994. Whether the sand layers from 2000 – 2002 are related to a storm in 2000 is unclear, because assignment of marsh age to the specific locations of sand layers may not be entirely correct. The variation in age within the two deposits is partly introduced by the boundaries between the age classes, which are rather coarse for this small scale.

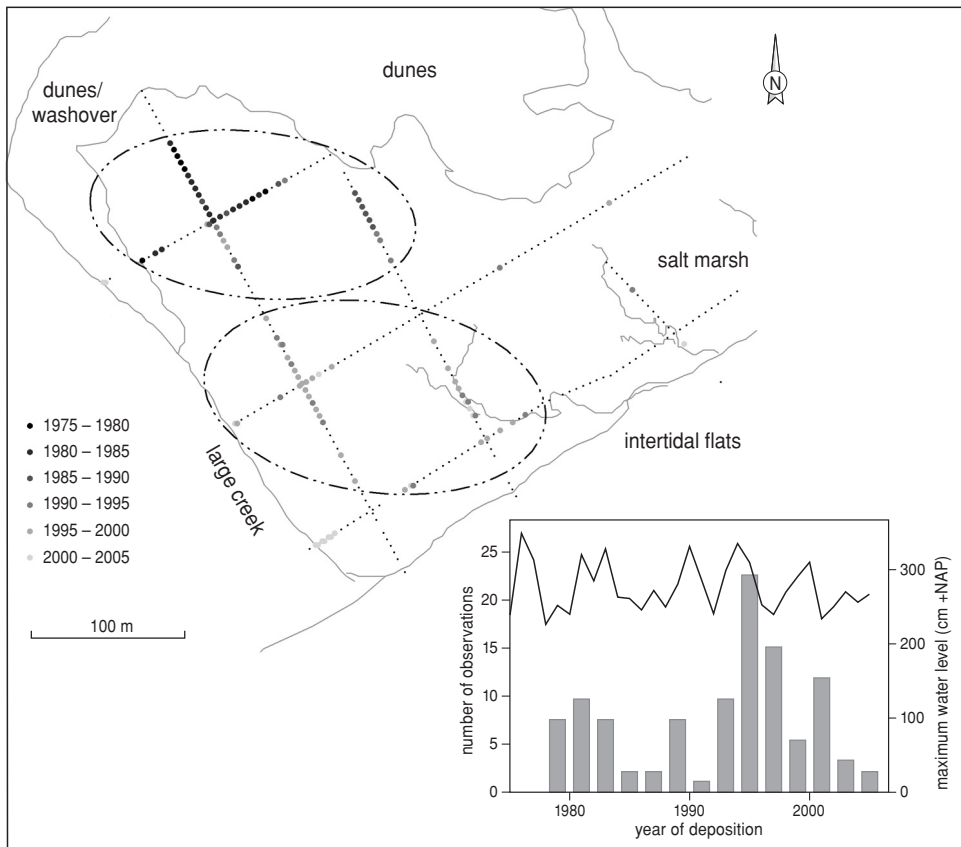


Figure 6.11. Map and histogram of the years of deposition of sand layers at the young catchment on Schiermonnikoog. The outlined areas are discussed in the text. The line in the graph represents yearly maximum recorded water levels (Rijkswaterstaat, 2008).

High-middle marsh

At the high and middle salt marsh, sand layers generally occur in patches of several metres across, in between larger areas without layers (Appendix 6C). In most cases, only one layer is present in the profile. Layer thickness varies mostly between patches. The locations and thickness of the layered patches are not related to small-scale topography in base or soil elevation. The proportion of the area containing layers and the volumetric contribution of the layers to the top layer varies between the transects (Appendix 6C and Figure 6.12). The volumetric contributions are, except for SCH_T1 and TERS_T1, all below ten percent. Along the chronosequence of Schiermonnikoog, these proportions are unrelated to marsh age. Transect TERS_T4, close to a large creek, shows relatively thick sand layers over almost half of the transect. The other Terschelling transects contain fewer sand layers. On Skallingen, the high-middle marsh contains hardly any sand layers.

Salt-marsh edge

A relatively high number of sand layers occur along the salt-marsh edge, especially when the edge is steep (Appendix 6B). The sand often form patches with a size of approximately 100 m perpendicular to the salt-marsh edge. The layers are often associated with a ridge in the underlying sand surface, suggesting a relation with this ridge. There is no consistency between the patterns of transition types and sand layers.

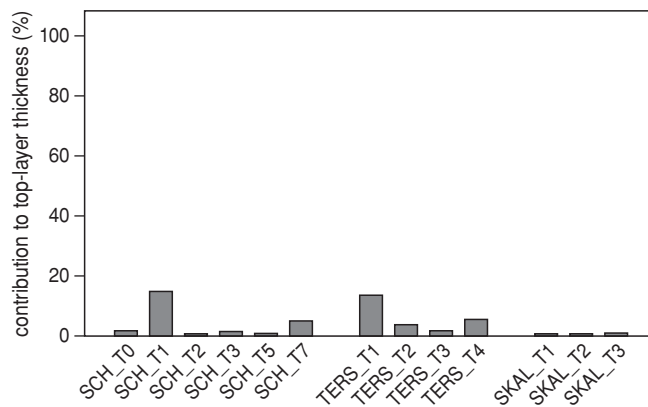


Figure 6.12. Volumetric contribution of sand layers to the top layer at the high-middle marsh of Schiermonnikoog, Terschelling and Skallingen.

6.4 Discussion

6.4.1 Initial salt-marsh development

The transformation from bare sand flat into barrier-island salt marsh is generally considered to take place under calm conditions (e.g. Olff et al, 1997). The sediment record indicates that salt marshes can also form when conditions under which sand can be transported still occur. The most dynamic areas during initial marsh formation are along the salt-marsh edge, the creeks and the dune foot. Based on this spatial pattern, there are several processes that may introduce the dynamics. Waves and currents coming from the intertidal flats cause dynamics at the young salt-marsh edge and current velocities are also high around developing creeks. Close to the dunes, the alternation of small contributions of aeolian (sand) and marine (mud) origin may give rise to gradual profiles. The role of overwash can be deduced from the increase in the proportion of sharp transitions after the construction of the artificial sand dike, as from the above processes, the sand dike only blocks the dynamics coming from the open North Sea. The subsequent increase in gradual transitions can be attributed to marsh areas that developed at relatively dynamic locations, i.e. southwards of the already existing marsh and east of the artificial sand dike. Finally, some of the gradual and intermediate transitions may result from bioturbation, in which burrowing organisms mix base and top layer. Such organisms are absent from the largest part of the salt marshes (hence the preservation of the layers, Van Straaten, 1954), but do occur at the high marsh (ants) and in the pioneer zone (organisms that are otherwise common on the intertidal flats). Which process is responsible for the gradual or intermediate transitions or the duration of the process at a specific location cannot be deduced from the individual cores.

Because barrier-island salt marshes develop their typical zonation and topography on a sloping base layer, the spatial distribution of dynamics is related to base elevation, leading to the general pattern of Figure 6.4. Apart from this pattern, the occurrence of the transition types is patchy on all scales. For example, the pattern of transitions types varies between and within the high-middle marsh locations, and even within 1 m². This suggests that in addition to the general forcing (waves, currents, washover, wind and bioturbation) there are controls on several (hierarchical) scales that determine the sedimentary result of the environmental conditions. For example, on the smallest scale this concerns temporarily changing irregularities of the salt-marsh surface, mainly created by vegetation (Van Straaten, 1954; Ehlers et al, 1993; Reineck and Gerdes, 1996).

6.4.2 Sand layers

Sand layers contribute to the growth of otherwise fine-grained salt marshes on barrier islands, on the island of Schiermonnikoog somewhat less than ten percent of the total deposits. The layers are most probably deposited during storm events, and resemble storm layers observed in marshes in Northern Ireland and Germany (Ehlers et al, 1993; Wheeler et al, 1999). On Schiermonnikoog, local sand deposits were observed at

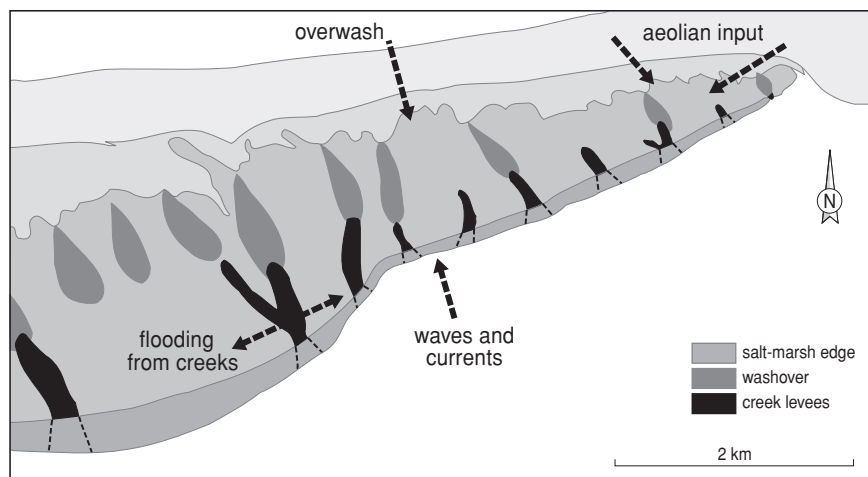


Figure 6.13. Schematically representation of dominant sand deposits on the salt marsh of Schiermonnikoog, based on measurement results.

the marsh surface after minor storms at the marsh edge and levees (pers. obs.). The ages of the layers indicate that storms capable of depositing sand on large areas of the salt marsh occur every decade or so. However, from the fact that the layers are not spatially continuous it can be concluded that the local dynamics and availability of sand finally determine whether a site receives sand or not. This is the same as for the transition types.

The locations where sand layers are found (Figure 6.13) are the same as reported fragmentary in literature. These areas coincide largely with those of the gradual transitions, even though layers and gradual transitions do often not occur together on the core level. The processes responsible for the deposition of the layers are therefore the same as for the dynamics during initial salt-marsh formation, except for bioturbation. The sources of the sand can be inferred from the locations of the layers and include all sand bodies around the marsh.

Most sand layers and the thickest sand deposits occur close to and along almost the entire salt-marsh edge (Figure 6.13). Here, sand is readily available for currents and waves from the intertidal flats, but is not transported far into the marsh. The distance the layers reach into the marsh is generally around hundred metres, and reaches up to a few hundred metres in case the marsh has been prograding. Sand layers are often associated with a ridge in the underlying sand surface. Probably, the conditions at such locations are so dynamic that in the young marsh phase, only sand is deposited and no fine-grained sediment. If a salt marsh advances in cyclic growth, relict edges with their associated layering may remain in the landscape (Wheeler et al, 1999; Van de Koppel et al, 2005; Pedersen and Bartholdy, 2007). Indications for such relict ridges exist in transects E1, E4, E5, E6 and E7 (Appendix 6B), which is consistent with the known ages of

the marsh. However, sand layers can also be deposited during advancing phases (transects E5, E6 and E7). Sand layers are therefore not necessarily an indication for past erosion of the marsh edge.

Sand layers along creeks consist of sand eroded from the creek bed or, in case the creek extends into an overwash channel, additionally of sand eroded from the seaward dunes and beach. The present dataset is not always detailed enough to outline the landward extent of washover deposits, but based on the present results and aerial photographs it is estimated that substantial deposits can reach up to approximately 200 m from the dunes and washover complexes. This is typical for barrier islands along the North Sea (Ehlers, 1988b; Nielsen and Nielsen, 2006a; Ten Haaf and Buijs, 2008). Overall, we estimate the area of marsh surface affected by overwash deposits to be around ten percent and the contribution to total marsh sedimentation in the order of a few percent at most. It should be noted, however, that this chapter only gives an indication of the contribution of sand to the salt-marsh area that is still capable of trapping fine-grained sediment. Areas that are buried under thick sand layers from overwash (up to 70 cm, Nielsen and Nielsen, 2006b; Ten Haaf and Buijs, 2008) will probably change into dunes and washover complexes and were not included.

It is hard to quantify the direct aeolian input from the dunes into the salt marsh, as sand layers are only limitedly present on sites with high base elevation. Part of the layers around washover channels may be formed by aeolian activity. Aeolian input onto the salt marsh was observed during strong easterly winds, when sand from the sand flat forming the distal end of the island blew into the young marshes of Schiermonnikoog. There it was captured by the vegetation and formed a low sand ridge close to the salt-marsh edge. This is an alternative mechanism for the formation of ridges and sand layers along the salt-marsh edge at the early stages of salt-marsh development.

Most marsh locations with sand layers contain only one layer. This indicates that the local environmental conditions at a site and/or the availability of sand change during marsh evolution. This is probably the result of lateral marsh growth (e.g. the southwards growth observed on Schiermonnikoog), creek development and ongoing dune formation. Only along the creeks and salt-marsh edge, the marsh remains open enough for the deposition of new sand layers during the entire lifetime of the marsh. The proportion of salt-marsh area on which sand was deposited increases after 1965. This can be explained by the locations where new marshes developed, changes in the frequency of extreme high tides (Figure 6.8) and perhaps reworking of the sand dike.

The present analysis has omitted layers of less than 0.5 cm thick and other textural variations within the top layer observed in part of the cores. The total number of sand deposits is therefore underestimated, but the total volumetric contribution of sand to the top layer will not be much higher, as the omitted layers are very thin. More detailed core analysis may reveal more information on past conditions in general.

6.5 Summary & conclusions

In this chapter we described the occurrence of sand in the otherwise fine-grained salt marshes on barrier islands, as indication for past conditions that were more dynamic than average. We found that a considerable part of the area of a salt marsh can initially form under conditions dynamic enough for the transport of sand, or experiencing considerable bioturbation.

High-energy events are preserved as sand layers. On the semi-natural salt marsh of this study, these sand layers are not continuous and occur at twenty percent of the salt-marsh area. The sand layers were deposited during a number of individual events in the 20th century, which could be related to recorded water levels. The method used for dating the layers is a much simplified one, so that the exact timing of the individual events could be estimated within at best five or ten years.

The locations of the sand layers are related to the marsh topography and reflect the sources of the sediment:

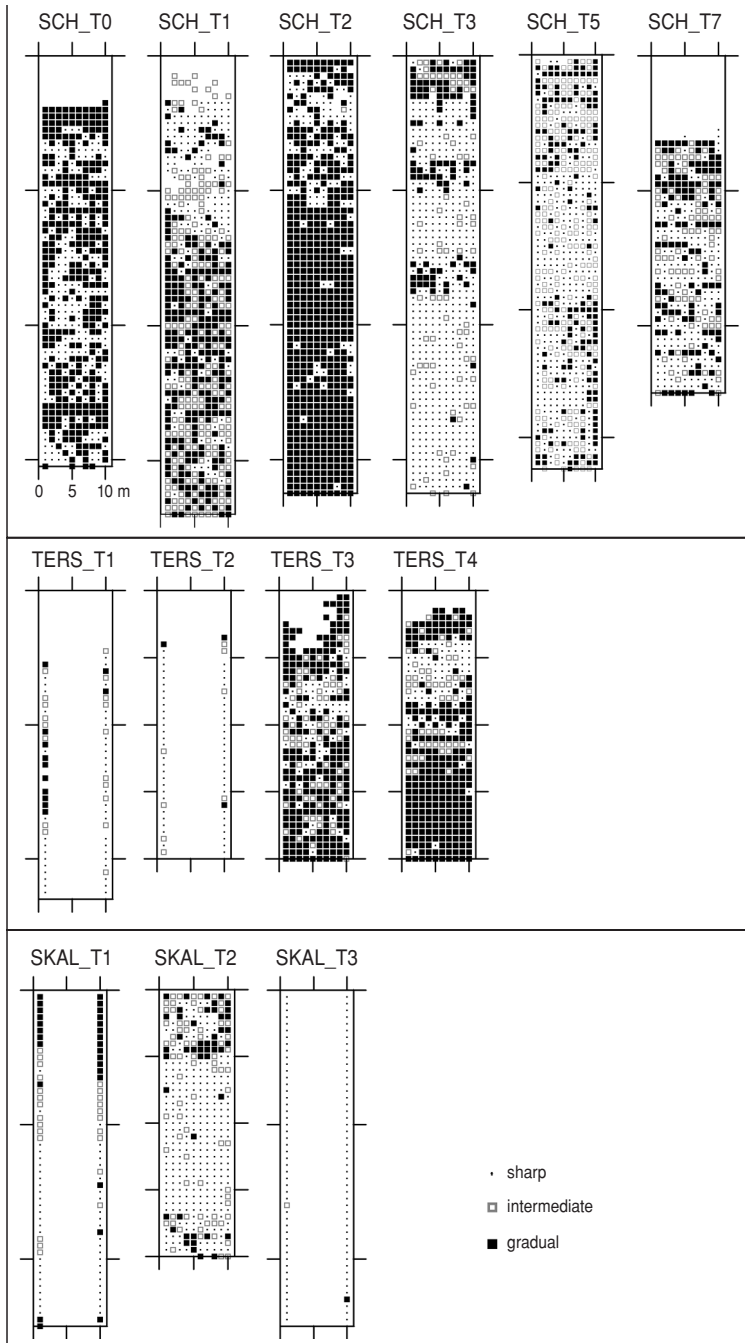
- Sand taken up from the intertidal flats is deposited on the marsh, close to the marsh edge, or transported into the marsh creeks;
- Sand eroded from the marsh creeks is deposited at and around creek levees;
- Overwash erodes sediment from the beach and dunes and deposits it onto the salt marsh;
- Sand from beach plains, dunes and washover deposits is blown into the salt marsh.

The building of artificial sand dikes, blocking transport from the open sea, has notably affected sand deposition and thus the local environmental conditions.

The overall contribution of sand to the salt marsh on Schiermonnikoog is less than ten percent of the volume of the top layer. The even smaller contribution of sand from overwash to the salt marsh (a few percent at most) means that active marshes probably do not rely on washover sediment to keep up with the present rate of sea-level rise. However, washover deposits may well be important in creating accommodation space and shelter for new marshes to develop.

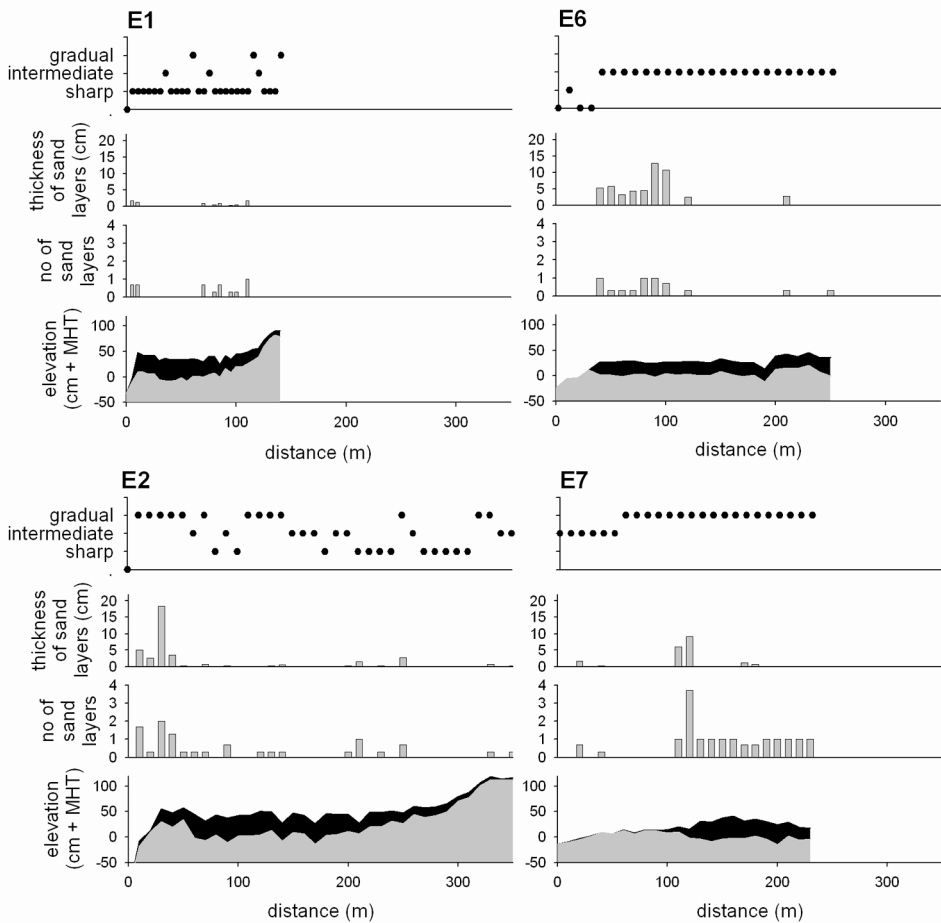
Appendix 6A.

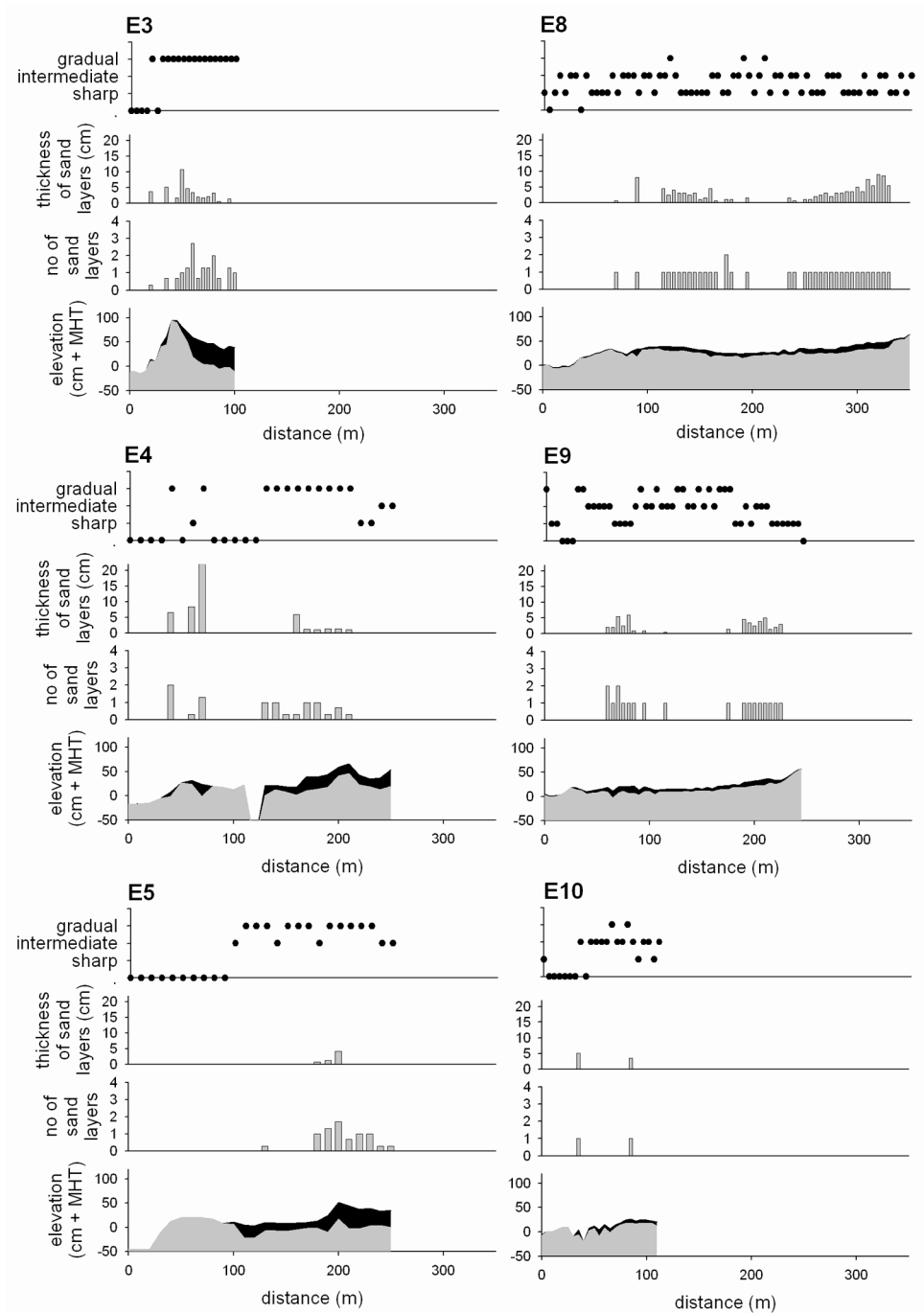
Maps of the distribution of transition type for the high-middle marsh sites on Schiermonnikoog (SCH_T0 – T7), Terschelling (TERS_T1 – T4) and Skallingen (SKAL_T1 – T3). Locations can be found in Figure 6.2. The upper part of each figure is located at the dune side.



Appendix 6B.

Cross-sections of the salt-marsh edge on Schiermonnikoog with the transition type (upper graphs), number of sand layers and the total thickness of those sand layers. For locations see Figure 6.2. The Wadden Sea (South) is to the left of the cross-sections. The black layer represents the top layer on top of the sand base (grey). Locations in the left panels are mainly erosive, right panels mainly accretionary.





Appendix 6C.

Maps of the total thickness of sand layers within the top layer at the high-middle marsh sites on Schiermonnikoog (SCH_T0 – T7), Terschelling (TERS_T1 – T4) and Skallingen (SKAL_T1 – T3). The upper part of each figure is located at the dune side.

